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1. Introduction

Loss data available in the literature regarding laminated magnetic materials excited by rotating fields are usually restricted to a few hundred Hz [1][2][3][4], a frequency range too restricted to predict the performance of high-speed electrical machines. In this paper we discuss loss measurements performed in low-carbon steel laminations under circular induction loci up to peak induction J_p = 1.7 T and frequency f = 1 kHz. It is a case of special interest, because the combination of low electrical resistivity and relevant thickness (d > 0.5 mm) makes the classical energy loss largely prevalent over the hysteresis and excess loss components beyond a few hundred Hz. The magnetization dynamics is affected, at the same time, by deep skin effect. We develop here a simple predicting model for the classical 2D energy loss in the presence of skin effect by introducing a simplified two-dimensional constitutive law in the electromagnetic diffusion equation, which is solved by a numerical method. The so calculated energy loss behavior shows good agreement with the measured dynamic losses.

2. Experimental

A three-phase magnetizer, especially designed through 3D Finite Element computations in order to attain technically relevant induction levels at high frequencies under two-dimensional excitation [5], was applied to the measurement of rotational losses in low-carbon steel sheets. An 80 mm diameter disk sample was made to precisely fit in the bore of the magnetizer, leaving a 1 mm air gap. The measurement of the two components of magnetic induction and effective field was performed according to the usual fieldmetric method [3]. A flat 20 mm × 20 mm multiturn calibrated H-coil centrally located on the surface of the sample was, in particular, used for the measurement of the effective value of the rotating field. Fig. 1 provides an example of rotational energy loss $W^{(ROT)}(J_p, f)$ behaviour versus polarization (0.2 T ≤ J_p ≤ 1.7 T), measured in the frequency range 2 Hz ≤ f ≤ 1 kHz on a 0.641 mm thick low carbon steel sheet (resistivity $\rho = 12.07 \cdot 10^{-8}$ Ω·m). It is noted the progressive disappearance of the maximum of the rotational loss versus J_p at frequencies beyond about f = 50 Hz. This effect descends from the corresponding rise of the classical loss component, eventually contributing for most of the measured loss and wiping out the role of the domain wall processes.

3. Skin effect model

The analysis of the rotational loss versus frequency, namely the loss separation procedure, reveals the appearance of skin effect beyond about 200 Hz. In order to quantitatively account for it and recover the actual features of the loss components under the non-uniform induction profile across the lamination thickness, the rotational classical loss is modelled by adopting a simplified rate-independent magnetic constitutive law ***B***(***H***), where the slightly anisotropic material is assimilated to an equivalent isotropic one. Thus, for any actual rotating induction vector ***B*** of defined modulus $|\boldsymbol{B}| = B_0$, a circular field locus $|\boldsymbol{H}_0|$ is found having same area as the actual one (Fig.2). This is obtained by means of a quasi-static measurement. The phase shift θ_{hyst} by which ***B*** lags behind $\boldsymbol{H}_0$ is the one associated with the hysteresis loss $W_h^{(ROT)} = 2\pi H_0 B_0 \cdot \sin\theta_{hyst}$. The non-linear vector diffusion equation across the sample cross-section, exploiting the previously found constitutive $\boldsymbol{B}(\boldsymbol{H}_0)$ law, is then solved [2]. A predictive example of high-frequency rotational energy loss $W^{(ROT)}$ is provided in Fig. 3 (f = 1 kHz). Here deep skin effect occurs in association with largely dominant classical loss component (predicted dashed line).

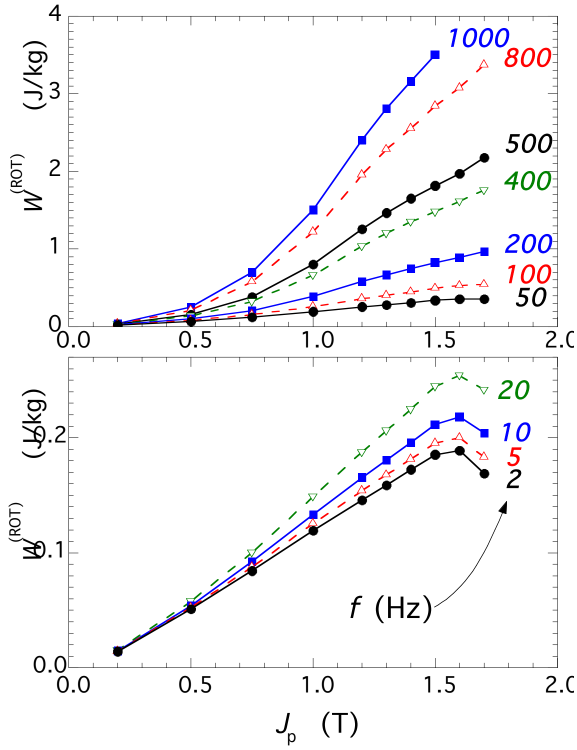

Fig. 1 - Experimental energy loss vs. J_p under circular polarization, with frequency ranging between 2 Hz and 1 kHz.

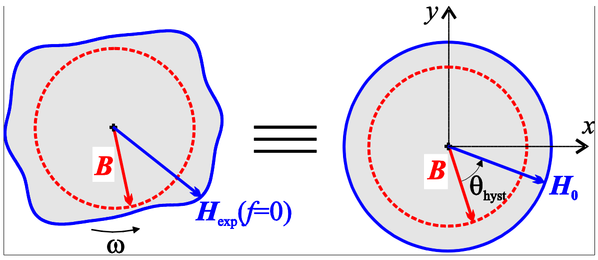

Fig. 2 - Derivation of the "equivalent" circular ***H*** locus emulating equivalent isotropic behaviour of the material. The gray regions have the same area. *ω* is the angular velocity.

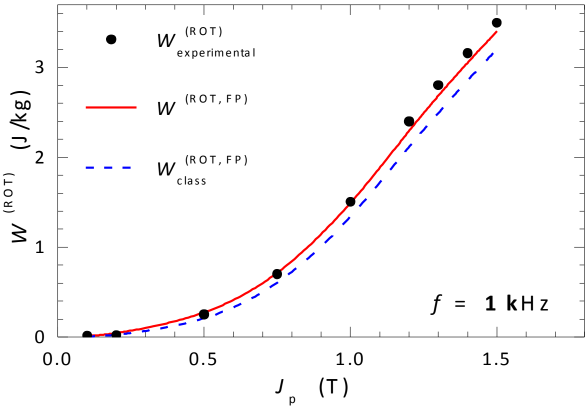

Fig. 3 - Experimental (symbols) and predicted rotational energy losses (total and classical) by the Fixed Point method versus polarization J_p at 1 kHz

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